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A management-oriented water quality model for data scarce catchments

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ABSTRACT

Due to the degeneration of water quality globally, water quality models could increasingly be utilised within water resource management. However, a lack of observed data as well as financial resources often constrain the number of potential water quality models that could practically be utilised. This study presents the Water Quality Systems Assessment Model (WQSAM). WQSAM directly utilises flow data generated by systems models to drive water quality simulations. The model subscribes to requisite simplicity by constraining the number of variables simulated as well as the processes represented to only those most important to water quality management, in this case, nutrients and salinity. The model application to the upper Olifants River catchment in South Africa is described. WQSAM was able to use the limited observed data to simulate representative frequency distributions of water quality, and the approach used within WQSAM was shown to be suitable for application to data scarce catchments.

Software and/or data availability

WQSAM is run from the SPATSIM modelling framework, which is freely downloadable from http://iwr.ru.ac.za/iwr/software/spatsim.php. To obtain WQSAM, contact Dr Andrew Slaughter, Institute for Water Research, Rhodes University, PO Box 94, Grahamstown, 6140, South Africa Email: a.slaughter@ru.ac.za. SPATSIM is windows-based and will run under recent and latest versions of Microsoft Windows on a desktop PC.

1. Introduction

Degradation of the water quality of fresh surface waters has become a global problem, particularly within developing countries which typically have less resources available to implement management of water quality (Zimmerman et al., 2008). This situation indicates the urgent need for water quality models as management tools. However, water quality models for managing water quality generally show less maturity than those for managing quantity. This is particularly true in South Africa, which has a relatively long and rich research history related to hydrological and systems models, having yielded two major hydrological models, namely the Agricultural Catchments Research Unit (ACRU) model (Schulze, 1989) and the Pitman Model (Pitman, 1973), their refinements and extensions (for example Hughes, 2004a,b; Hughes et al., 2010), as well as two systems models, the Water Resources Modelling Platform (WReMP) (Mallory et al., 2011) and the Water Resources Yield Model (WRYM) (Basson et al., 1994). The determination of the ecological Reserve for rivers in South Africa, which is the water quantity and quality that should be 'reserved' to maintain the aquatic ecosystem, has been facilitated from a quantity point of view through relatively sophisticated tools and methodologies, such as that developed by Hughes (2004a,b). In comparison, research on water quality modelling tools specific for use in South Africa is a relatively young and emerging science, and although some initial progress has been made, using mostly statistical regression relationships between flow and water quality, for example Malan and Day (2002), no mechanistic water quality models have gained traction within water resource management in South Africa as yet. Key to management of water quality in South Africa is understanding the relationship between flow and water quality. This is because flow is the primary driver of water quality, and directly affects water quality as a transporting mechanism of non-point source water quality loads from the catchment, by diluting water quality instream and by driving the residence time of water quality loads in surface waters. The relationship between flow and water quality in South Africa in particular is very

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important, as a mostly semi-arid country with an extreme hydrological regime.

South Africa is typical of most developing countries in that there is a general scarcity of hydrological data, and this situation is continually worsening as more historical gauges go off-line due to a lack of resources. The scarcity of data is exacerbated in regards to water quality data, as these data are relatively expensive and difficult to measure, and there are many more variables to consider. Given the aforementioned context of water resource management in South Africa, a water quality model suited for use within South African water resource management would need to be able to provide simulations of water quality that are sufficiently accurate for use within water resource management, using the available historical monitoring data.

With the goal of developing a water quality model in mind, development on the Water Quality Systems Assessment Model (WQSAM) was initiated during 2012. WQSAM adheres to the principle of requite simplicity (Stirzaker et al., 2010) by only representing water quality variables that are of concern to management, and only the water quality processes that account for the majority of the spatial and temporal variation of those variables. In addition, WQSAM aims to produce water quality simulations that provide a representative frequency distribution of water quality that can be related to risks of particular water quality thresholds being exceeded. It is important to note that WQSAM does not aim to provide accurate time series predictions of water quality, as its focus is on providing frequency distributions of water quality. As mentioned before, this approach was adopted because of the management focus of the model, and because this approach can be achieved using a relatively simple model. WQSAM additionally aims to directly model the relationships between flow and water quality, and in this regard, accepts flow input from the routinely used systems models (WReMP or WRYM). This approach was taken because no other systems models are established within water resource management in South Africa, and this approach would further facilitate the use of WQSAM within practical water resource management. The long history of the use of WReMP and WRYM within water resource management in South Africa also means that accurate model setups of these models already exist for many catchments.

At present, there is no other water quality model that has been designed to directly and seamlessly link to the aforementioned systems models, which is why the development of WQSAM fills an important gap within water quality management in South Africa. This approach also reaffirms the management focus of WQSAM, as the model design primarily considers factors to facilitate the use of the model in water resource management.

The current paper describes the application of the WQSAM model to the Olifants River Catchment in South Africa for historical conditions, and aims to demonstrate that WQSAM is able to represent water quality variation of salinity and nutrients within a data scarce catchment with sufficient accuracy for the purposes of water quality management. The Olifants River Catchment was chosen for two important reasons: this catchment is economically important, hosting intensive agriculture and mining activities, and the catchment is arguably the most modified catchment in South Africa, both in terms of flow and water quality. Due to the extensive exploitation of the catchment, the systems representation of the catchment is complex, offering a challenging water quality modelling case study.

As initial model functionality, water quality simulations in WQSAM focussed on eutrophication and salinisation, as these are the two most problematic water quality problems in South Africa. In addition, the limited available historical monitoring data includes indicators of eutrophication and salinisation. Also, since the aim of WQSAM was to be relatively simple, the model focussed on the most important water quality variables from a management point of view. Although some hydrological components of WQSAM have been described previously (e.g., Slaughter et al., 2015), the present report is the first of WQSAM applied to a catchment as a water quality model.

2. Model and study area

2.1. Model description

2.1.1. Model representation of catchments and linkages

The systems representation used within WQSAM by necessity mirrors that of the water quantity systems models (WRYM or WReMP), as WQSAM uses the flows generated by these systems models to drive water quality simulations. Typically, sub-catchments and reservoirs are represented as nodes distributed across the modelled catchment. Fig. 1 represents the nodes and channels of the subcatchments leading into Middleburg Dam, which is a portion of the study area used in the present study (see Fig. 3). The spatial extent of the catchment represented by each node depends on the level of detail the catchment was modelled in, which depends on water management requirements. The flow within the water quality systems models is routed from upstream nodes to downstream nodes along the channels connecting the nodes.

Nodes in the modelled catchment are connected by channels, typically divided into a particular number of input and output channels. Particular channel numbers within the input and output channels are reserved for particular types of flow, for example incremental inflow, return flow, downstream releases and reservoir compensation flows. This allows WQSAM to recognise the types of flow in the system and how they affect water quality.

The definitions of river and reservoir nodes were as according to the systems model. If a particular node had a storage value, meaning that some water is held back and not automatically routed downstream over each time step, then that node was considered a reservoir. These nodes are typically triangular shaped in the systems diagram. Therefore, the entire system consisted of a collection of river and reservoir nodes.

2.1.2. Conceptual structure of the model

WQSAM can be described conceptually as consisting of several tiers of functionality. Fig. 2 shows the structure of these tiers, and

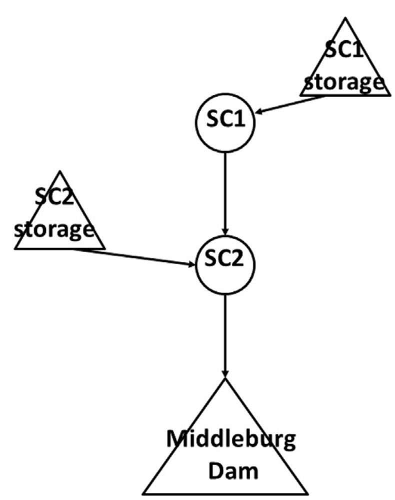

Fig. 1. Nodal structure representing the subcatchments and linkages into Middleburg Dam. 'SC' stands for subcatchment. Within each subcatchment, storage nodes (triangles) represent the cumulative water storages within the subcatchment.